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Quantum sensor for photon counting in particle physics experiments

D. Bowring

APT Seminar

18 August 2020

Acknowledgements

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- FNAL: D. Bowring, A. Chou, M. Hassan, M. Hollister, N. Kurinsky, A. Sonnenschein
- IIT/FNAL: R. Khatiwada, J. Yu
- U. Chicago: A. Agrawal, A. Dixit, D. Schuster
- Penn State: M. Zaidel
- UMN: G. Spahn

and collaboration with:

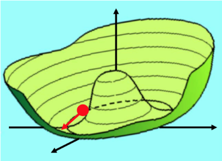
- NIST/JILA: K. Lehnert
- the ADMX collaboration
- Yale: R. Maruyama, S. Cahn
- JHU: D. Speller

Overview & Talk Goals

- Very brief introduction to axions
- Current axion search strategies
- Overlap with accelerator science/tech interests?
- We require low-noise single photon counting $\rightarrow$ QIS detector tech
- Our work

This talk will highlight some of the points of common interest with the accelerator community.

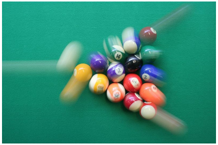
The axion is a proposed solution to the strong CP problem.



- Peccei & Quinn, Phys. Rev. Lett **38**, 1440, 1977.
- Spontaneously broken symmetry $\rightarrow$ new boson
- Axion field "tilts" the degenerate QCD vacuum, resulting in a CP-conserving minimum.
- $\theta = \theta_0 e^{\imath m_a t}; \qquad \theta_0 = \sqrt{\frac{2\rho_a}{\Lambda^4_{\mathrm{QCD}}}} = 3.7 \times 10^{-19}$
- P. Sikivie's "Pool table analogy": `https://arxiv.org/pdf/hep-ph/9506229.pdf`

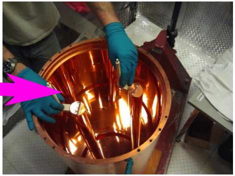
Axions and WIMPs

WIMPs scatter as quanta



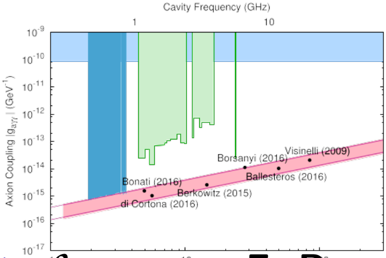
- WIMP-nucleon scattering detector strategies
- Mass $\sim$ 10s-100s of GeV?

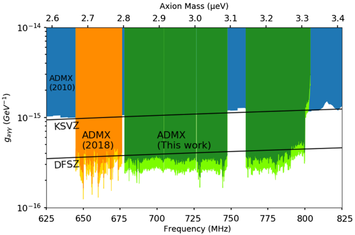
Axions scatter as classical waves



- Coherently oscillating "clouds"
- $h/p \sim 100$ m
- Phase coherence over $\sim$ms.
- $\mu ev < m_a <$ meV

Axion mass is only loosely constrained by theory/measurement.





- $\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$
- DFSZ model for $a \rightarrow \gamma\gamma$ detection relevant to DM axions. Points are predictions from theory.
- **ADMX has reached DFSZ-compatible sensitivity: PRL 124, 101303 (2020).**

How to detect axions?

Maxwell's equations (theorist units):

$$\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} = \mathbf{J}_{\mathrm{EM}}$$
$$\nabla \cdot \mathbf{E} = \rho_{\mathrm{EM}}$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \cdot \mathbf{B} = 0$$

Axions represent an extra source term in Maxwell's equations:

$$\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} = g \left(\mathbf{E} \times \nabla a - \mathbf{B} \frac{\partial a}{\partial t} \right) + \mathbf{J}_{\mathrm{EM}}$$
$$\nabla \cdot \mathbf{E} = \rho_{\mathrm{EM}} + g \mathbf{B} \cdot \nabla a$$

`http://arxiv.org/pdf/1310.8545.pdf`

How do you detect axions?

$$\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} = g\left(\mathbf{E} \times \nabla a - \mathbf{B}\frac{\partial a}{\partial t}\right) + \mathbf{J}_{\mathrm{EM}}$$

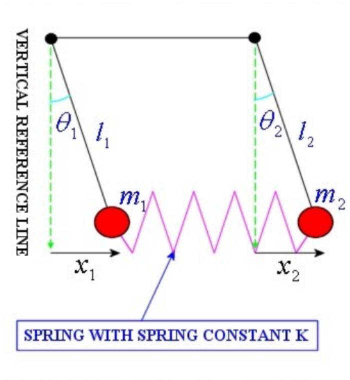
$$\nabla \cdot \mathbf{E} = \rho_{\mathrm{EM}} + g\mathbf{B} \cdot \nabla a$$

In the presence of a strong magnetic field B_0, axions give us an exotic current density $J_a = -gB_0\dot{a}$. Then we have a detection strategy:

1. Use a multi-Tesla B-field to convert axions into virtual photons.
2. Use a resonator to accumulate/detect the faint signal ($< 10^{-21}$ W) from photons.
3. Make the cavity *tunable*.

Resonant axion detection: an analogy

Accelerators use RF cavities to impart energy to particle beams. This is just the inverse problem: using RF cavities to extract energy from weak sources.



Signal power and SNR drive haloscope design.

$$P \approx 2.2 \times 10^{-23}\ \mathrm{W} \cdot \left(\frac{\rho_a}{0.45\ \mathrm{GeV/cm^3}}\right)\left(\frac{f_a}{740\ \mathrm{MHz}}\right)$$
$$\times \left(\frac{g_{a\gamma\gamma}}{0.36}\right)^2 \left(\frac{V}{136\ \mathrm{L}}\right)\left(\frac{B}{7.6\ \mathrm{T}}\right)^2\left(\frac{Q}{3\times 10^4}\right)\left(\frac{C}{0.4}\right)$$

Dicke radiometer equation explains design constraints:

$$SNR = \frac{P}{kT_s}\sqrt{\frac{t}{\Delta f}}$$

- Signal power is limited: $P \propto B^2 V$
- $t \lesssim 100$ s for realistic run schedules
- System noise temperature $T_s = T_{\mathrm{phys}} + T_N$
- At the quantum limit, $T_N \to 48$ mK at 1 GHz

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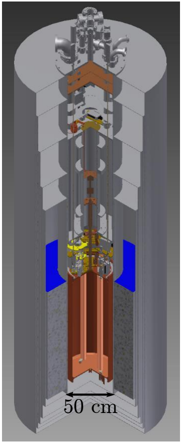
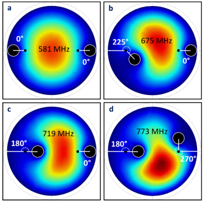
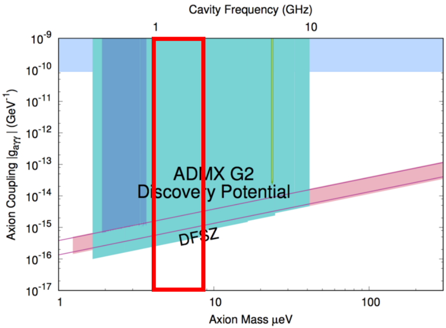
ADMX Overview

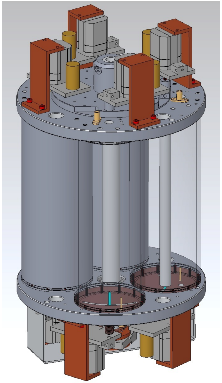


- 500 MHz - 1 GHz cavity
- 7 T solenoid
- ^{3}He-^{4}He dilution refrigerator
- Quantum-limited amplification



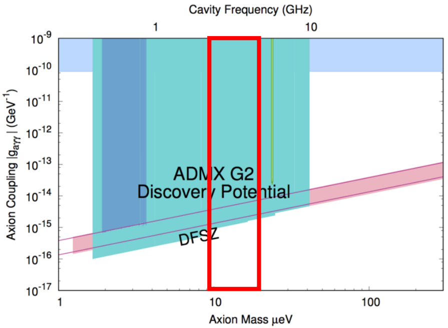
How to scale in frequency?





Fabrication underway for 4-cavity array, 1-2 GHz.

How to scale in frequency?



Fermilab concept for $\geq$ 2 GHz cavity.

Perhaps you've already noticed some points of common interest between axion hunters and accelerator builders. Let's discuss in more depth.

Superconducting magnets play a significant role in our experimental planning. Recall $P_{\text{sig}} \propto B^2 V$.

Solenoids Present & Future

CICC = Cable-In-Conduit Conductor
SRC = Stabilized Rutherford-Cable
Mono = Monolithic Conductor

B_0^2V (T^2m^3)	Magnet	Application/ Technology	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
12000	*ITER CS*	*Fusion/Sn CICC*	*Cadarache*	*13*	*2.6*	*13*	*6400*	*>500*
5300	CMS	Detector/Ti SRC	CERN	3.8	6	13	2660	>458[1]
650	Tore Supra	Fusion/Ti Mono Ventilated	Cadarache	9	1.8	3	600	
430	*Iseult*	*MRI/Ti SRC*	*CEA*	*11.75*	*1*	*4*	*338*	
320	ITER CSMC	Fusion/Sn CICC	JAEA	13	1.1	2	640	>50[2]
290	*60 T out*	*HF/HTS CICC*	*MagLab*	*42*	*0.4*	*1.5*	*1100*	
250	*Magnex*	*MRI/Mono*	*Minnesota*	*10.5*	*0.88*	*3*	*286*	*7.8*
190	Magnex	MRI/Mono	Juelich	9.4	0.9	3	190	
70	45 T out	HF/Nb_3Sn CICC	MagLab	14	0.7	1	100	14
12	ADMX	Axion/NbTi mono	U Wash	7	0.5	1.1	14	0.4
5	900 MHz	NMR/Sn mono	MagLab	21.1	0.11	0.6	40	15

[1]Materials only per BBC/CERN.
[2]US inner module $50M per Minervini

Italics indicates a magnet not yet operational 6

Slide credit: M. Bird, NHMFL ADMX Magnet Workshop, 2018

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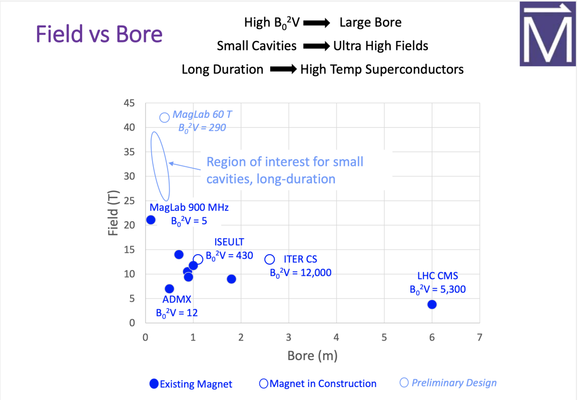
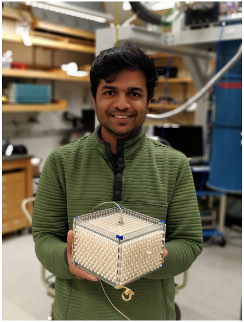


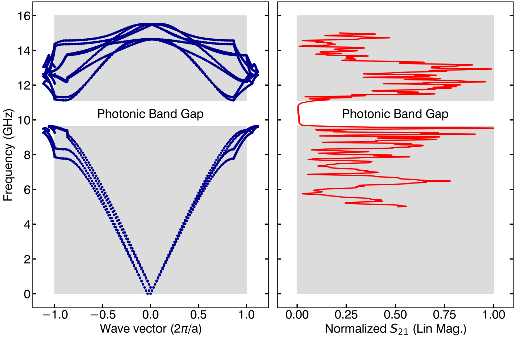
Slide credit: M. Bird, NHMFL ADMX Magnet Workshop, 2018

We also need high-Q, normal-conducting cavities.

- Recall $P_{\mathrm{sig}} \propto Q$.
- Axion linewidth corresponds to $Q \sim 10^6$.
- Typical performance w/ OFHC copper is $O(10^4)$ at 1 GHz.

Ankur Agrawal is building PBG structures at U. Chicago.





Alumina rods in a regular lattice; center defect forms cavity.

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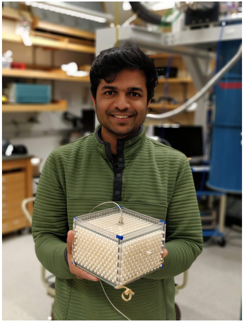
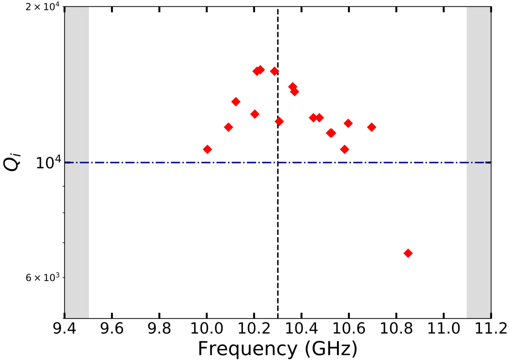




These results are from 2019, with improvements coming online very soon.

Combining power from multiple, tunable cavities is also an interesting problem.

Cross-correlation signal processing for axion and WISP dark matter searches

Ben T. McAllister,[1,*] Stephen R. Parker,[1] Eugene N. Ivanov,[2] and Michael E. Tobar[1,†]

[1] *ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia*

[2] *School of Physics, The University of Western Australia, Crawley 6009, Australia*

(Dated: March 7, 2019)

The search for dark matter is of fundamental importance to our understanding of the universe. Weakly-Interacting Slim Particles (WISPs) such as axions and hidden sector photons (HSPs) are well motivated candidates for the dark matter. Some of the most sensitive and mature experiments to detect WISPs rely on microwave cavities, and the detection of weak photon signals. It is often suggested to power combine multiple cavities, which creates a host of technical concerns. We outline a scheme based on cross-correlation for effectively power combining cavities and increasing the signal-to-noise ratio of a candidate WISP signal.

McAllister et al, arXiv:1510.05775 (2019).

Finally, there are some interesting challenges for cavity designers.

- $P \propto C \sim 0.4$
- $$C = \frac{|\int_V dV \vec{E} \cdot \vec{B_0}|^2}{B_0^2 V \int dV \epsilon |E|^2}$$
- S. Asztalos et al., PRD 64, 092003 (2001).
- This is especially interesting as the cavity tuning approaches a mode crossing.

Back to the central problem: low-noise, low-rate microwave photon detection. Let's do some quantum mechanics to understand the category of problem we have here.

Lower noise limit of one photon per resolved mode.

From Clerk *et al.*, `https://arxiv.org/abs/0810.4729`:

- Apply a gain G to a bosonic input mode a: $b = \sqrt{G}a + F$, for added noise $\mathcal{F}$.
- $[b, b^\dagger] = G[a, a^\dagger] + [F, F^\dagger]$
- Apply the generalized uncertainty principle: $(\Delta b)^2 \geq G(\Delta a)^2 + \frac{1}{2}|G - 1|$
- In the large-gain limit,

$$\frac{(\Delta b)^2}{G} \geq (\Delta a)^2 + \frac{1}{2}$$

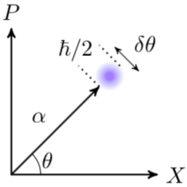
Linear amplifiers suffer from irreducible QM noise.

- **Standard Quantum Limit (SQL):** one photon per resolved mode
- Expressed as a rate:

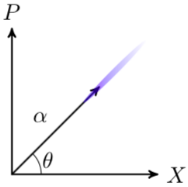
$$\frac{dN_{\mathrm{SQL}}}{dt} = 1 \times \Delta f = \frac{2f}{Q_a}$$

- The axion width means $Q_a \sim 10^6$.
- This is just a consequence of the Heisenberg uncertainty principle.

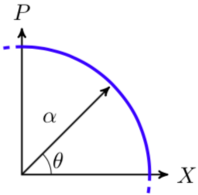
“Squeezed states” can help solve this problem.



(a) Coherent state, $\Delta P \Delta X \gtrsim \hbar/2$

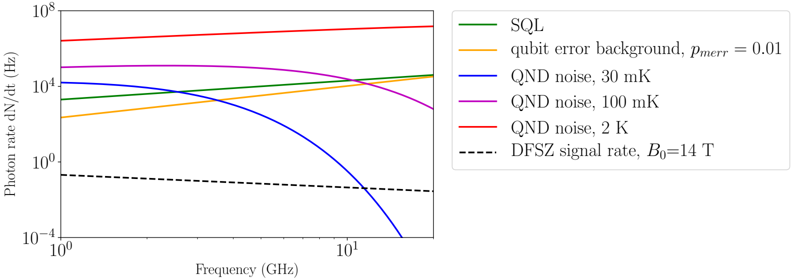


(b) Squeeze in phase, θ



(c) Quantum nondemolition

Quantum nondemolition



- We can circumvent the SQL using a technique called *quantum nondemolition*.
- If we are successful, the dominant noise source will be the system's blackbody photons.

Stark Effect in quantum mechanics

Hydrogen atom perturbed by an electric field $\vec{E} = E\hat{z}$:

$$H = \frac{p^2}{2m_e} - \frac{e^2}{4\pi\epsilon r} + e|\vec{E}|z.$$

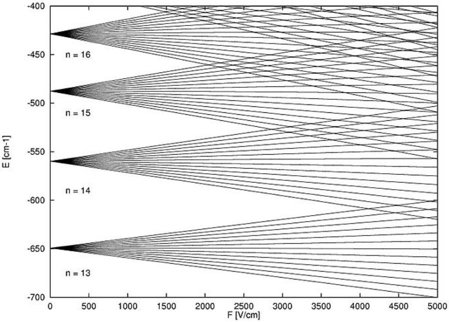
Solve using perturbation theory to find

$$\Delta E = -\frac{1}{2}\alpha|\vec{E}|^2$$

where

$$\alpha = 2e^2 \sum \frac{|\langle n\ell m|z|n'\ell' m\rangle|^2}{E_{n'\ell' m'} - E_{n\ell m}}$$

The consequence of this is a field-dependent level-splitting.



M. Courtney, `commons.wikimedia.org/wiki/File:Hfspec1.jpg`

Similar problem: two-level "atom" weakly coupled to a harmonic oscillator

$$H = \hbar\omega_r(a^\dagger a + 1/2) + \hbar\omega_q\sigma_z/2 + \frac{\hbar g^2}{\Delta}(a^\dagger a + 1/2)\sigma_z$$

with $\Delta = \omega_q - \omega_r$. We'll assume weak coupling $g \ll \Delta$.

- Weak coupling $\rightarrow$ photon not absorbed by "atom".
- Note that the final term commutes with the others.
- This is the *Jaynes-Cummings Hamiltonian*.
- Number operator $\hat{N} = a^\dagger a + \sigma_z$ commutes with H!

Rewrite JC Hamiltonian suggestively.

$$H = \hbar\omega_r(a^\dagger a + 1/2) + \hbar\omega_q\sigma_z/2 + \frac{\hbar g^2}{\Delta}(a^\dagger a + 1/2)\sigma_z$$

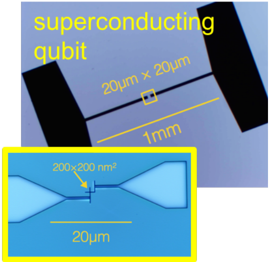
$$H = \hbar\left(\omega_r + \frac{g^2\sigma_z}{\Delta}\right)(a^\dagger a + 1/2) + \hbar\omega_q\sigma_z/2$$

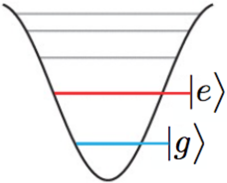
so $\omega_r \to \omega_r \pm g^2/\Delta$. Or, similarly,

$$H = \hbar\omega_r(a^\dagger a + 1/2) + \frac{\hbar}{2}\left(\omega_q + 2\frac{\hbar g^2}{\Delta}a^\dagger a + \frac{g^2}{\Delta}\right)\sigma_z.$$

This is effectively an AC Stark shift in the atom transition frequency $\omega_q \to \omega_q + 2\bar{n}g^2/\Delta$.

Choice of “atoms” not limited to atoms.

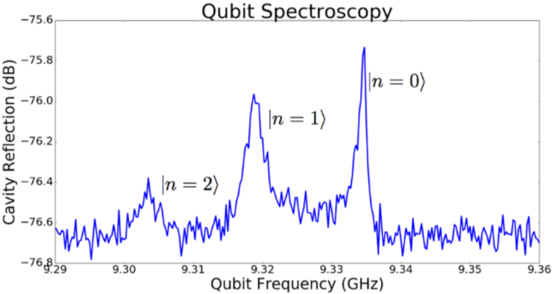




$$\omega_q = E_1 - E_0$$

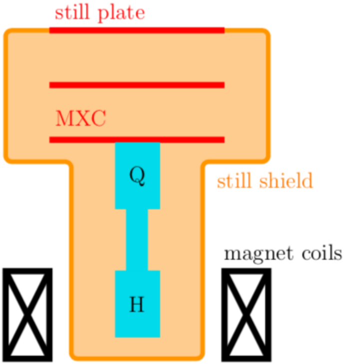
- Anharmonicity: energy levels are “addressable”.

Probing the qubit state $|n\rangle$ by observing a frequency shift in the cavity



Observation of $|n\rangle$ through 15 MHz dispersive frequency shift.

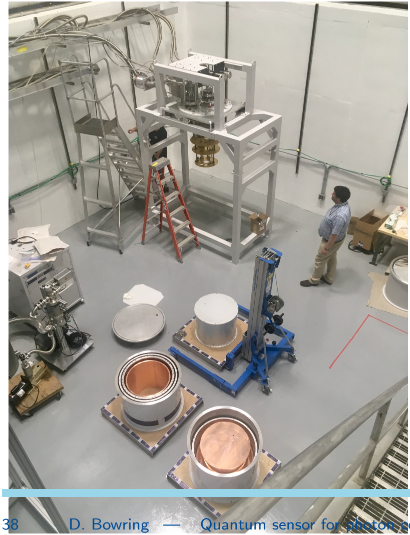
Measurement cartoon



Thermal background Boltzmann-suppressed via 10 mK He dilution refrigerator, funded through Fermilab LDRD.

In practice, what does this look like?

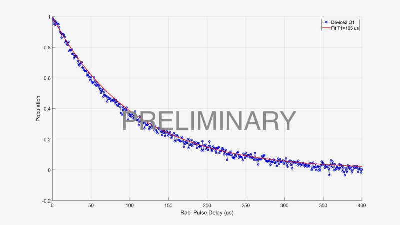
We have a dilution refrigerator runinng at SiDet, in Lab B.

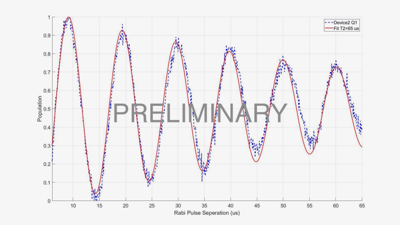


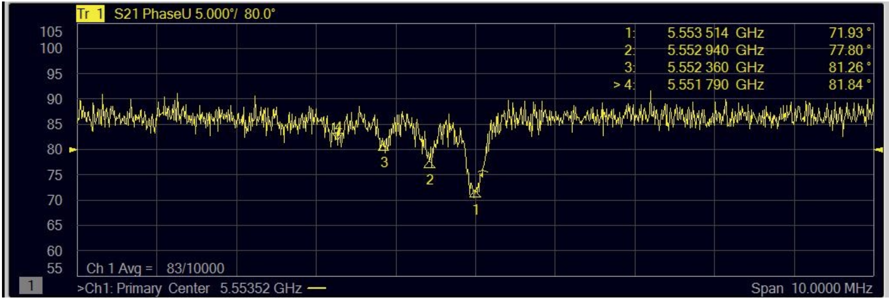
Current work

- Devices fabricated at U. Chicago by Schuster group.
- Characterization in Lab B dilution fridge is ongoing.
- Also under development: further ways to increase signal / suppress noise power.
  - PBG cavity development (see above)
  - Multi-qubit readout
  - TWPA implementation
  - Line filtering
  - Radiation-induced quasiparticle burst studies
  - Magnet integration

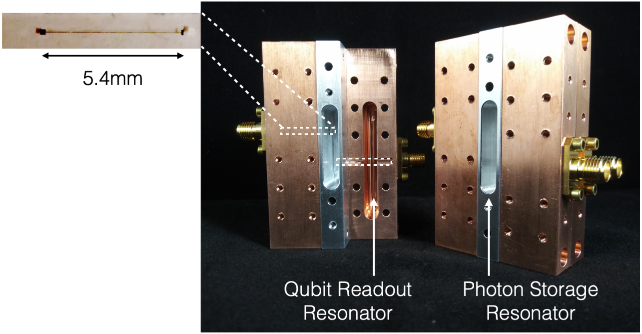
Device characterization is routine now.







A. Dixit is working on multi-qubit measurements at U. Chicago



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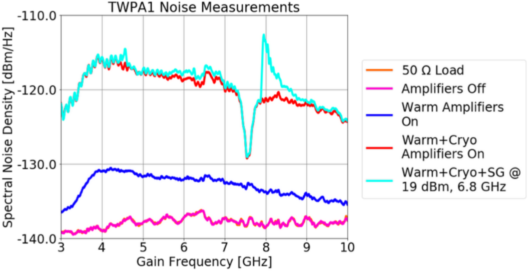
- Qubit parity error $p_{\mathrm{err}} \approx 0.01$.
- Require N qubit agreement: $p_{\mathrm{err}} \rightarrow (0.01)^N$.

TWPA for quantum-limited, broadband readout

- Thanks to MIT Lincon Labs and IARPA for providing us with devices
- C. Macklin, Science 350.6258 (2015).
- R. Khatiwada, M. Hassan, D. Bowring (FNAL) and **M. Zaidel (Penn State)** automated TWPA readout this summer. Preliminary results:



In progress: improved filtering of thermal photons

- F. Yan et al., PRL 120, 260504 (2018).
- "Eccosorb" epoxy and its derivative filters are standard tools for IR filtering.
- In partnership with N. Kurinsky (FNAL) and G. Spahn (UMN) we're developing in-house filter sources.

Radiation-induced quasiparticle bursts?

- c.f. N. Kurinsky, Dark Matter Efforts at Fermilab, August 11, 2020 Users' Meeting.
- Broad interest in a very-low-background test stand for characterizing superconducting circuits.
- e.g. L. Cardani et al., arXiv 2005.02286

Can't find axions without a magnet...

- 14 T solenoid procured from Oxford Instruments
- Testing phase now? Expect delivery in Fall 2020, thanks to COVID.

Conclusions

Thanks for your attention!

- Axion searches require low-noise, single-microwave-photon readout.
- Quantum computing has developed these tools for us already.
- Goal is to take this technology and deploy it in the context of a particle physics experiment.